AIRCOOLED DIESEL-ENGINE APPRAISAL

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THE AUTHOR compares aircooled and liquid-cooled diesel engines from the several points of view, including: Plumbing difficulties, antifreeze requirements, bulk (hp per cu ft), weight (lb per hp), fan power and quantity of cooling air required, noise, costs, operation and maintenance.

Present-day aircooled diesel engines can be divided into four categories: those for industrial installations, small sized engines for agricultural applications, medium sized multipurpose engines, and large engines for military uses. Several examples of each type are discussed.

The author reports that because of their advantages in space utilization and adaptability to a wide range of temperatures, the aircooled engine is coming into greater and greater use.

EVER since Rudolph Diesel invented the combustion cycle that bears his name, engineers have been striving to design better and better versions of this engine. Many designs of diesel engines have been built and tested and many facets of these designs have been thoroughly covered by the literature; notably combustion, lubrication, intake and exhaust systems, and the like. One subject, however, has received relatively little attention during the more than 50 years of diesel-engine development and this is the question of aircooling versus liquid cooling of diesel engines. (See Additional References.)

When this subject is put forth the question naturally arises: "Why aircooling?" Admittedly, there are several applications where aircooling is obviously not practical. In general, these are marine installations or industrial installations alongside of free water supplies where liquid cooling is inexpensive and, therefore, desirable, and where at the same time the heat can be disposed of without capital cost in coolers. Likewise, there are applications such as motorcycles, aircraft, and military vehicles where aircooling has become the accepted standard, since it is the logical choice in the existing environment. Aircooling also becomes very attractive where nature has given us either extreme temperatures to contend with or reduced the available water supply to practically nil, such as in desert or arctic areas. For 25 years we have been building aircooled gasoline engines for use by Army Ordnance in track-laying military vehicles. These engines have been highly successful in meeting the special requirements of combat vehicles, namely:

1. Minimum bulk for the total power package, including all cooling of the engine and transmission.
2. Minimum power losses for cooling.
3. Adequate cooling of the power package buried in an engine compartment with all openings on top and with considerable airflow restrictions from ar-

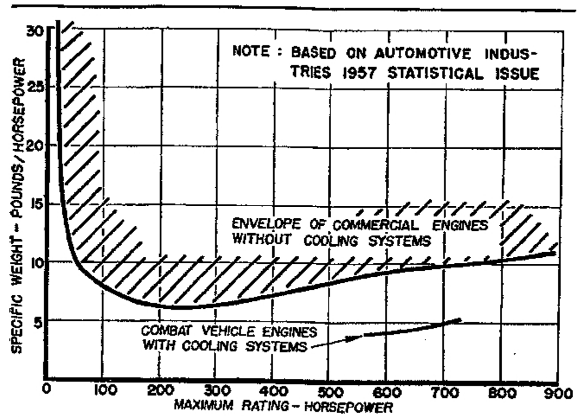


Fig. 1—Weight comparison, combat vehicle versus commercial engines

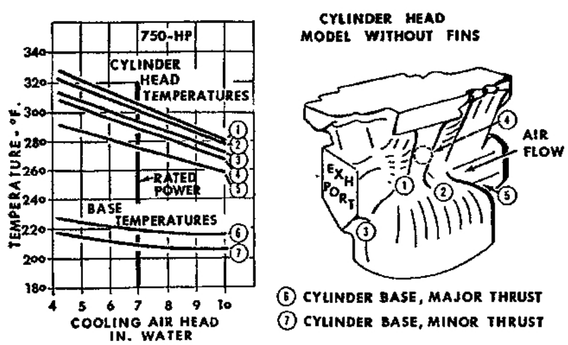


Fig. 2—5¾-in. bore diesel cylinder cooling

Table 1—Comparison of Aircooled and Liquid-Cooled Engines

	Military Vehicles, Advantage for		Commercial Vehicles, Advantage for	
	Air	Liquid	Air	Liquid
Plumbing Difficulties	X		X	
Antifreeze Requirements	X		X	
Bulk, hp per cu ft	X		Equal	
Weight, lb per HP	X		Equal	
Fan Power and Quantity of Cooling Air Required	X		Equal	
Noise		X		X
Costs	Equal		Equal	
Operation and Maintenance	X		X	
Lubricating Oil Cooler	Equal		Equal	
Lubricating Oil Cleanliness	X		X	
Net Specific Fuel Consumption	Equal		Equal	
Cylinder Wear	Equal		Equal	

mored bulletproof airflow grilles.

4. Operation under the extreme climatic conditions of desert and arctic.

5. Improved logistics due to elimination of two items of supply—water and antifreeze.

We have recently developed an aircooled diesel engine as a replacement for the aircooled gasoline engines.[1] It was a relatively small step from gasoline to diesel in the technical sense, but one that paid dividends in reduced fuel consumption compared to the gasoline predecessor.

The military turned to the diesel principle as a replacement for the gasoline engine[1] since this type of engine would contribute substantially to the overall logistic problem. Miles per gallon for a diesel engine have been well-established at 60% more than that of a gasoline engine; hence, a reduced supply problem or a larger radius of action is possible. The change involves the addition of one extra item of fuel supply; but the possibility of a diesel engine running on gasoline or turbine fuel, which is already being supplied for other purposes, is being examined.

Liquid Cooled versus Aircooled Engines

Table 1 summarizes the more apparent items in the comparison of liquid-cooled and aircooled engine principles and states an evaluation based on our experience.

Plumbing Difficulties—Elimination of plumbing difficulties is an obvious advantage of aircooled engines. Liquid-cooled engines for military purposes have as many as 40 hose clamp connections (the average V-8 passenger car or truck engine has about 12, each a potential point of leakage. In addition, liquid-cooled engines have cylinder head and liner gaskets which are potential trouble spots. These items, together with the water pump, plugs, and other gaskets constitute hundreds of places for leakage troubles. Service department records show that about 20% of all engine failures in liquid-cooled engines are caused by cooling system faults. Nearly all of these are of a type which can be eliminated by the aircooled engine. Offsetting the leakage disadvantage of liquid-cooled engines, there is a sheet metal problem with aircooled engines. This sheet metal does not require tight joints, however. The attachment and stiffening methods must be carefully worked out to obtain long life and ease of assembly.

Antifreeze—Antifreeze problems are listed in Table 1 as a separate item, since they do become quite severe in a great many regions of the world. Some fleet operators are so concerned with the uncertainty of ordinary antifreeze protection that they prefer to completely drain the cooling system in cold weather rather than risk a freeze-up. Others use an equally undesirable procedure of allowing the engine to idle for hours so that it never can cool down. In addition to the freezing problem, liquid-cooled engines suffer from corrosion and clogging of the radiator and cooling system as a result of decomposition of the antifreeze with scale and rust forming in the jackets. The initial incentive to the use of aircooled engines is normally this one item in conjunction with the plumbing problem, and there is no doubt that the aircooled engine has the advantage in this feature without an offsetting disadvantage.

Bulk—Ordinarily cylinder spacing is dictated by the thickness of the cylinder walls and the liquid-cooling space between cylinder bores. Aircooled engines require considerably more space between cylinder bores because of the necessary height of the fins and this means that the overall length of the engine is greater. This length differential between the two types is being reduced by modern trends to high bmep because the large boost in specific output demands stiffer and, therefore, larger crankshafts in proportion to cylinder bores. The net result of these modern trends toward high specific output is that cylinder spacing of both aircooled and liquid-

[1] SAE Transactions, Vol. 65, 1957, pp. 641–656: "Continental 750-Horsepower Aircooled Diesel Engine," by H. H. Haas and E. R. Klinge.

cooled engines is now dictated by crankshaft and crankcase structure rather than space between cylinder bores.

Three classifications of usage can then be discerned:

1. High-performance packages, such as armored fighting vehicles. For these applications, the liquid-cooled engines themselves may be slightly smaller, but the power package turns out to be considerably larger than the aircooled package when the cooling system and ducts are added for desert cooling in the restricted space of armored hulls.
2. Moderate performance applications, such as trucks and earthmoving machinery. In these cases, the more compact liquid-cooled designs are often selected where package bulks may be similar between aircooled and liquid-cooled installations.
3. Low output industrial uses where the aircooled package is undoubtedly larger, but it is also likely that bulk considerations are not very important weighed against such matters as trouble-free running, availability of coolant, and the like.

Weight—General statements regarding comparative weights of liquid-cooled and aircooled engines are difficult to support, as the predominant influence is the objectives of the design and the applications intended. There is a tendency for aircooled engines to be lighter because of the necessary extensive use of aluminum. But this margin partially disappears if liquid-cooled engines are designed with a similar policy and material usage. Because of the need to include radiators and coolant in the weight analysis, liquid-cooled engines are usually found to be at a slight disadvantage on weight compared to an aircooled engine. Fig. 1 shows published weight information of both aircooled and liquid-cooled types presently available, but makes no attempt to evaluate future types. It shows that the demands of military usage leads to engines of lower weight than does the commercial types.

Fan Power and Cooling Air Quantity—It is a comman misconception that aircooled engines use more power for cooling and a higher quantity of air than do the liquid-cooled types. The reverse is usually found in military applications while commercial applications of aircooled engines are usually about equal to the liquid-cooled engines.

Fig. 2 shows typical temperatures measured on one of our 5¾-in. bore aircooled diesel cylinders. If a median temperature of the fins is taken as 260 F and the ambient air on a hot day is 125 F, the temperature differential between the metal and the cooling air is 135 F. This compares with a differential of only 55 F between the radiator (180 F) and the cooling air of liquid-cooled military engines if no pressure system is used. Fig. 3 is a pictorial representation of these conditions, showing the extra equipment required by the liquid-cooled engine.

There are advantages to operating a liquid-cooling system under pressure, in which case the temperature differential between the coolant and air is increased. In general, the military are opposed to pressure systems because of the greater problems of sealing and the danger of losing all of the coolant in cases where the pressure valve pops open. In certain commercial applications it is common practice to use pressure systems of 4–7 psi (corresponding to temperatures of 224–232 F), in which case the airflow and cooling power for the liquid-cooled system approaches the values of the aircooled type.

Fig. 4 gives a group of examples from the combat military field of liquid-cooled and aircooled vehicle installations with the airflow and cooling power compared on the design basis of 125 F cooling air for aircooling and 90–100 F cooling air for liquid-cooling. In this illustration the unshaded extension at the upper part of the liquid-cooled engine bars represents the magnitude to which the airflow and power for cooling would reach for a 125 F day if additional space were available, as would be the case in a normal installation for nonmilitary use. These examples are chosen because the installations were particularly comparable in that vehicle horsepower requirements and other factors were nearly identical. This experience shows that the average power and airflow are down about 50% for the aircooled type under desert conditions. In the commercial field where radiator size is not a factor, these gains are not shown.

There are additional benefits in the case of military vehicles with buried power plants, because concurrently with the reduction in fan power, the reduced airflow permits a saving in grille sizes and duct work necessary for handling the cooling air.

The military vehicle, as opposed to the industrial engine, is designed with wide ambient temperature in mind, since the standard hot day is specified at

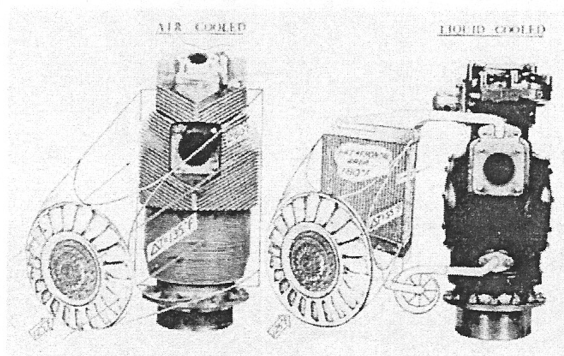


Fig. 3—Comparison of typical cooling systems

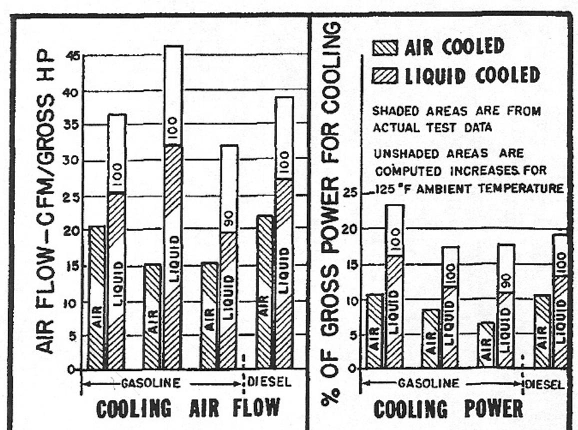


Fig. 4—Military vehicle cooling test results

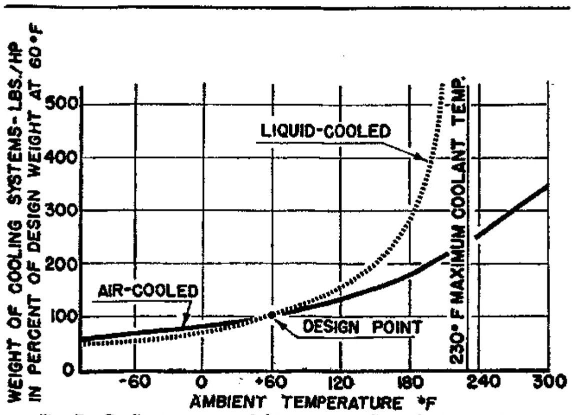


Fig. 5—Cooling system weight versus cooling air temperature

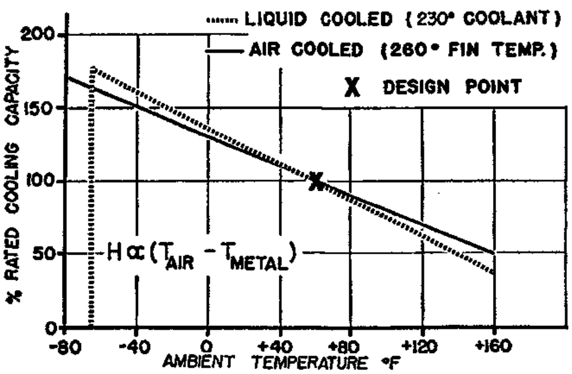


Fig. 6—Cooling system capacity

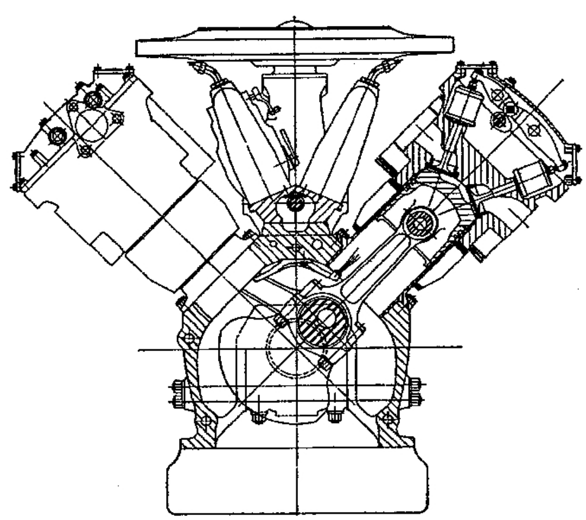


Fig. 7—Fan arrangement on V-type aircooled engine

Table 2—Comparison of Coarse and Fine Finning

	Coarse Finning	Fine Finning
Bore, In.	4.33	5.75
Stroke, In.	4.33	5.75
Displacement, cu in.	63.8	149.1
Hp per Cyl	12	80
Speed, rpm	1800	2400
Hp per Cu In Displacement	0.188	0.536
Bmep	83	177
Cooling Surface, sq ft	3	36
Cooling Surface Internal Cyl and Head Surface	5.85	39.8

125 F ambient and the engine compartment temperature can then be 140 F but with modern airborne equipment this same vehicle could, inside of a few hours, be transported to the arctic with temperatures of −65 F or lower. It is of interest, therefore, to compare the two types of cooling on the basis of such a range of ambient temperatures. Fig. 5 shows the relative change in weight of cooling system for an engine of constant output as the coolant temperature is varied for each type of coolant, based on each being called 100% at the design point of 60 F. It is apparent that for temperatures below 60 F the liquid-cooled system has advantage over the aircooled engine. Full advantage cannot be taken of this point in practice, however, since even present-day antifreezes will begin to slush at −65 F.

On the high temperature side, an increase in weight of about 50% occurs in the liquid system if an ambient temperature of 120 F is to be encountered. The aircooled engine requires only about 30% increase in weight of the cooling system for the same ambient temperature.

Another feature of the two types of engines, which is worthy of discussion, is their response to variations in ambient temperatures. Fig. 6 shows the variation in cooling capacity of aircooled and liquid-cooled engines from the standard design day of 60 F ambient to the extremes of cooling air ambient temperature of −65 to 120 F. It is very apparent that if both cooling systems are designed for 100% capacity at the same ambient temperature, the one having the highest metal temperature in contact with the cooling air will also have the highest reserve when the cooling air temperature increases. The liquid-cooled engine with its maximum temperature of 230 F (pressurized system) at the radiator can cool only at 65% of its designed capacity on a 120 F day, while the aircooled engine still has 70% of its capacity. It may also be noted that these figures are not extreme conditions by any means. Our practice is to design engines with adequate cooling capacity for ambient temperatures of 140 F. Even though this increase in capacity is small, there are installations where it can become quite important.

A natural question to ask at this point is, "Does not this condition penalize the aircooled engine under conditions of arctic operation, when the ambient temperatures are extremely low?" The answer is found in a variety of ways, such as to install a thermostat providing for recirculation of the cooling air in the same manner as liquid is recirculated in the liquid-cooled type. Likewise, shutters to control or limit the flow of cooling air are used, similar to devices used on many liquid-cooled vehicles. The best method, however, is to provide for speed-control mechanism to stop or control the speed of the cooling fan. This method not only maintains a correct engine operating temperature but also reduces the fan power losses; also, it is coming into use for liquid-cooled engines as well.

The ideal coolant should have a high specific heat, a freezing point well below the lowest operating temperature, a boiling point of at least 300 F, be chemically inert, and be available in unlimited

quantities throughout the world. Except for its high specific heat, water does not meet these qualifications; neither does any other liquid. However, air does more nearly meet the requirements of the ideal coolant.

Aircooled engines, particularly V-type engines, lend themselves to utilization of otherwise wasted space for installation of the fans and fan drives (Fig. 7). With this type of arrangement there is no increase in bulk to accommodate the cooling system. Liquid-cooled engines, on the other hand, must be supplemented by large radiators, fans, fan drives, and a piping system. These items add materially to both the bulk and weight of the complete power package. In addition, there is the weight of the coolant itself, which is no mean item.

The two cylinders (Fig. 8) illustrate the difference made in cylinder finning and the resultant change in performance made possible by better finning. The sectional view showing the coarse finning represents a type which is in harmony with the service required and illustrates a very useful class of engine. This engine and the fine finned cylinder are compared to show what is necessary in the way of cooling fin design to make a high output type cylinder. Many other features, such as supercharging and high-strength materials, are necessary in addition to fine finning to achieve the high output shown. The fine finned type is admittedly more expensive, but the increase in power permitted more than offsets the cost increase, so that the result in terms of cost per horsepower is in favor of the fine finned construction. (See Table 2).

Fig. 9 shows the variation of relative cooling power required with the variation of relative weight of the cooling equipment. Marine engines may be considered special cases in that their cooling plant weight becomes very large by comparison with other engines, since these units may be thought to have a whole ocean or lake at their disposal as part of their cooling system. Aircooled military engines are a compromise between cooling power sacrificed on the one hand and bulk increase in an effort to reduce cooling power losses on the other.

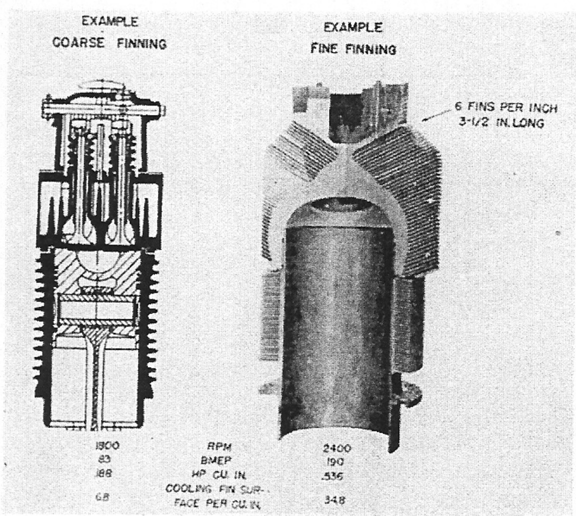


Fig. 8—Comparison of extremes of aircooling cylinder design

Commercial vehicles are different than high-performance military engines since civilian economy dictates quite a different sort of compromise, because relative bulk of the cooling unit is not as important for trucks by comparison with military engines. In general, low relative cooling power means high relative size of cooling system and vice versa.

A description of a typical aircooled engine fan performance is included to show that use of high pressure drops in cooling air systems does not imply low performance fans. This typical assembly (Fig. 10) is a 25-in. tip diameter fan with a 15½-in. hub, or a hub-tip ratio of 0.62. It operates at 5600 rpm and moves 15,000 cfm of 240 F air against 13 in. of water static pressure. The maximum axial width of

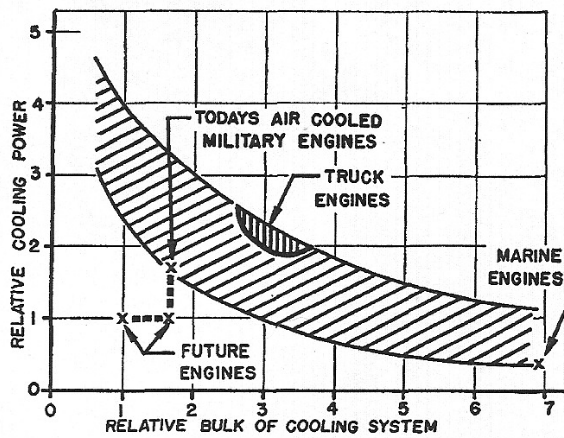


Fig. 9—Effect of size of cooling system on power requirements

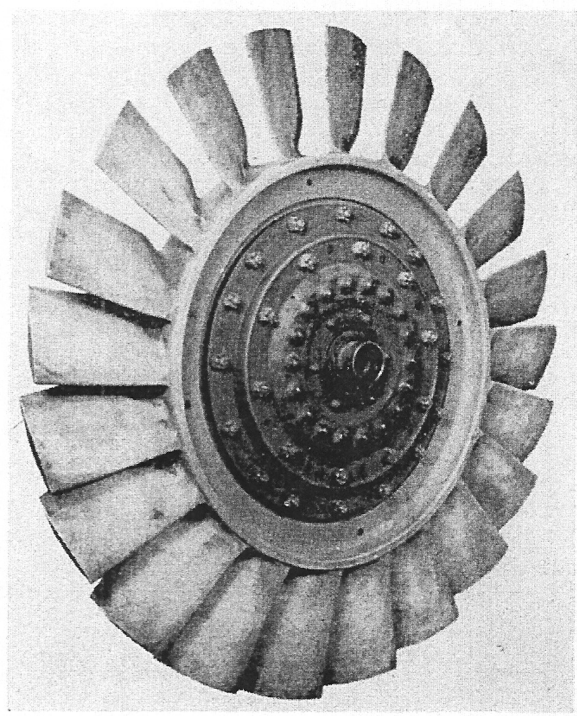


Fig. 10—Aircooled engine fan and clutch

the fan rotor is 2.4 in. Fig. 11 shows the typical fan test wind tunnel performance of this fan rotor at 5600 rpm. The comparatively flat static pressure performance curve at the design point is noteworthy, since this means that operation off design conditions is feasible.

The dimensions of this rotor and its stator were chosen physically to maintain a minimum overall engine height with an airflow velocity about 115 fps through the fan annulus and to allow the mounting of a centrifugally actuated clutch which will unload during water immersion. If increased fan efficiency is required, increase in stator height to improve diffusion is effective.

Noise—Aircooled engines are often more noisy than liquid-cooled designs and frequently this is because of fan noise. Military installation of aircooled engines ordinarily use half of the fan pressure differential in overcoming the duct system resistance and the other half for pressure drop across the cylinders. This demands high tip speed for fans, which in turn is conducive to high noise. A way of greatly reducing sound from the fan is by uneven spacing of the fan blades.

Fig. 12 shows the sound spectra of three fan rotors having 21, 22, and 24 blades. On the 21- and 24-bladed fans, the blades are unevenly spaced around the hub; the 22 blades are evenly spaced. Fig. 12 shows that the energy peaks are higher for the 22 evenly spaced blades in comparison with the unevenly spaced blade fans, and this reduction of sound energy is very noticeable to the human ear. In addition, prominent fan noises have been dispersed and masked by sound hash in the place of distinct reinforcing harmonics. It is the dispersion and masking of predominant frequencies that makes the unevenly spaced design an improvement.

Additional noise considerations are those sounds produced by the valve gear, piston slap, and fuel injector, which are essentially equal in the two types. Minor advantage for the liquid-cooled principle results from some damping of sound by the water layer and extra metal wall.

Costs—As manufacturers of both aircooled and liquid-cooled engines, we have found that there is little, if any, cost differential between liquid-cooled and aircooled engines, given identical conditions. Fig. 13 gives relative sales price of engines in three industries. No attempt is made in this chart to compensate for variation in accessories, materials, life requirements, or other factors which affect cost as indicated in the explanatory table included. The point to be made from this chart is that aircooled types are not greatly different from liquid-cooled engines in cost per horsepower.

Since 50% of the weight of the aircooled engine is of parts of the same type and workmanship as on liquid-cooled engines, this much of the comparison will show equal cost. The accessories comprise an additional 10% of the engine weight and the same type of accessories may be used on either engine. This leaves 40% of the weight to be compared for costs. Our aircooled engine uses aluminum for the cylinder head and crankcase as compared to cast iron for the liquid-cooled engine. Examination of the cost of these materials shows that there is no reason to claim extra cost because aluminum is more expensive on a per pound basis. Aluminum parts of equal strength to cast iron are usually lighter and aluminum is generally more economical to machine so that the net result is often a lower cost. Also, scrap losses are usually less, since the individual cylinder construction of the aircooled engine does not condemn five good cylinders because of one defective spot. The size and design of many aircooled engine parts permits casting by permanent

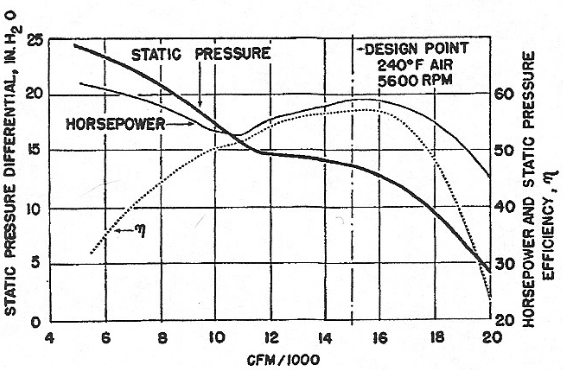


Fig. 11—Performance of typical aircooled engine fan

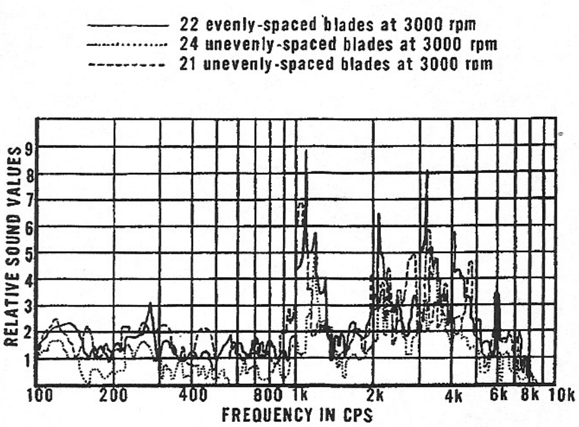
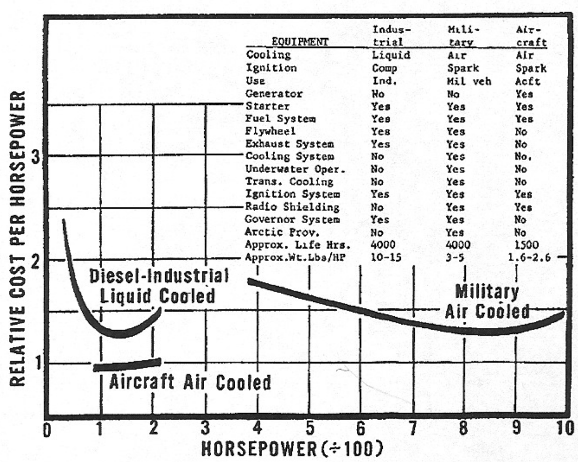


Fig. 12—Sound spectra of typical aircooled engine fans



EQUIPMENT	Industrial	Military	Aircraft
Cooling	Liquid	Air	Air
Ignition	Comp	Spark	Spark
Use	Ind.	Mil veh	Acft
Generator	No	No	Yes
Starter	Yes	Yes	Yes
Fuel System	Yes	Yes	Yes
Flywheel	Yes	Yes	No
Exhaust System	Yes	Yes	No
Cooling System	No	Yes	No.
Underwater Oper.	No	Yes	No
Trans. Cooling	No	Yes	No
Ignition System	Yes	Yes	Yes
Radio Shielding	No	Yes	Yes
Governor System	Yes	Yes	No
Arctic Prov.	No	Yes	No
Approx. Life Hrs.	4000	4000	1500
Approx.Wt.Lbs/HP	10-15	3-5	1.6-2.6

Fig. 13—Relative sales price

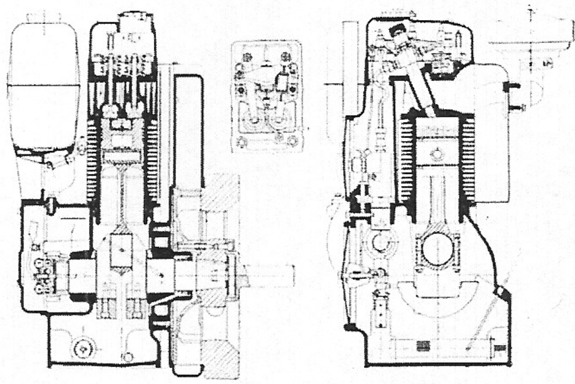


Fig. 14—Lister 6-hp, 1-cyl engine

Table 3—Average Characteristics of Aircooled Diesel Engines

	Industrial[a]	Small Size Tractor[b]	Medium Size Multipurpose[c]	High Performance Military[d]
Bore, in.	3.0–4.5	2.7–3.4	3.5–4.7	5.1–6.1
Stroke, in.	3.0–4.5	3.5–3.8	4.4–5.5	5.5–6.9
Displacement per Cyl, cu in.	21–80	20–33	47–90	113–204
Horsepower per Cyl	2.5–12	6–12	12–28	27–62
Number of Cyl	1–8	1–2	1–12	9–16
Horsepower per Engine	2.5–96	6–24	12–330	245–750
Speed, rpm	1200–1800	2000–3000	2000–2500	2000–2400
Horsepower per cu in.	0.12–0.19	0.26–0.36	0.23–0.32	0.24–0.42
Lb/Horsepower	106–20	19–13	49–9	7–2.9
Bmep, psi	60–85	43–65	78–122	86–138
Piston Speed, ft per min	750–1300	1350–1850	1650–2120	2000–2300
		Characteristic of Type		
Cycle	4-stroke	2-stroke	4-stroke	4-stroke
Illustration Figs.	14 and 15	16–19	20–24	25–29
Combustion Chambers		Divided or open-chamber combustion systems used in all classes.		

[a] Low output, low cost engines for industrial installations.
[b] Small Size, light weight engines, principally for agricultural applications.
[c] Medium Size, large production engine families for a wide range of automotive, agricultural, and industrial applications.
[d] Large Size, high performance engine families essentially for military applications.

mold or die casting methods which can give still further economies.

Because of the individual cylinder construction, the automation system of production can be economically applied at a smaller engine unit rate than would be the case with an enbloc design. Combined with the smaller size of the individual cylinder unit, this leads to automation with all of its benefits.

It is concluded that the cost of aircooled vehicle engines when produced at low yearly rates may be equal to and, at high yearly rates, less than the cost of an equivalent liquid-cooled engine with its cooling system on a dollars per horsepower basis.

Operation and Maintenance—The usual experience is that aircooled engines warmup quicker and operate with higher cylinder wall temperatures at light load than do liquid-cooled engines. The reduced warmup period is beneficial as far as cylinder bore wear is concerned and helps to reduce the possibility of fuel or condensation contaminating the lubricating oil and forming acid or sludge. This characteristic is especially valuable when it is necessary to operate with fuels which contain a high percentage of sulphur.

Many test comparisons of aircooled and liquid-cooled engines show that the fuel consumption is unaffected by the cooling type. Fuel consumption is more importantly influenced by combustion principles and friction losses.

It is obvious from an operator's point of view, that it is advantageous to omit the water pump, radiator, and many coolant seals and gaskets. Not only do these parts never cause an interruption in service, but no spares for them need to be carried in stock, and they never need to be maintained nor replaced. The omission of water and antifreeze are of obvious benefit when applied to engines that are operating in unattended stations, where the operators are inexperienced, or where more than one crew operates the same piece of equipment.

The basic design pattern for most aircooled engines is the individual cylinder. This feature makes for smaller parts to store as spare parts and reduces the amount of money invested in spare parts.

Aircooled Diesel Engine

Over the years there has been a considerable background of aircooled diesel experience, especially in Europe, and some previously published data on the results are included here for ease of reference.[2]

The small and medium size high-speed diesel engine was fostered in Europe after World War I due to the need for economical and low cost power plants in automotive and industrial applications. In 1927, Austro Daimler in Austria offered the first aircooled diesel engine for public sale and since that time other companies have provided a continuing program of engine development.

During World War II, the aircooled engine was used to a rapidly increasing extent by the ground forces of both parties. The German Army operated aircooled gasoline and diesel engines in cars, trucks, tractors, and tanks, and the U. S. Army in tanks only. During this period, the outstanding reliability of the aircooling system under the most severe conditions in the arctic, as well as in the desert, was proved most conclusively.

After World War II a sequence of aircooled diesel engines appeared on the European market. Because of the unusually wide diversity of design, any comparison of different models produces confusion. However, it seems that intended use and characteristic features permit a classification which may lead to a better evaluation of the various models. The distinguishing features of the four classifications are given in Table 3.

A more detailed description of the features common to each category follows, illustrated by representative engine models of various makes.

Low Output, Low Cost Engines for Industrial Installations—The characteristic features are:

1. Four cycle.
2. Three to twelve hp per cyl.
3. Low bmep (60–85 psi).
4. Low Speed (1000–2000 rpm).
5. One to eight cyl.
6. Long life (5000 hr minimum, without overhaul).
7. Simple, sturdy, but rather bulky and heavy structure.
8. Wide use of cast iron for cylinder head, cylinder liner, crankcase, and other parts.

Engines of this kind show wide acceptance overseas, where their reliability and ease of maintenance are appreciated. Most British aircooled diesel engines belong to this group. The Lister engine (Fig. 14) built in Great Britain, is a typical representa-

[2] Prepared by Dr. H. H. Haas, Chief Engineer, Diesels, Continental Aviation and Engineering Corp.

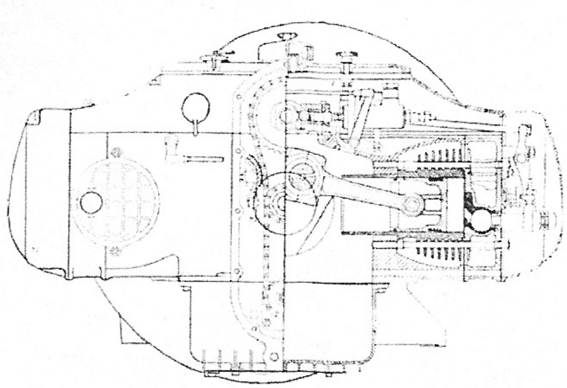


Fig. 15—Enfield 13.3-hp, 2-cyl engine

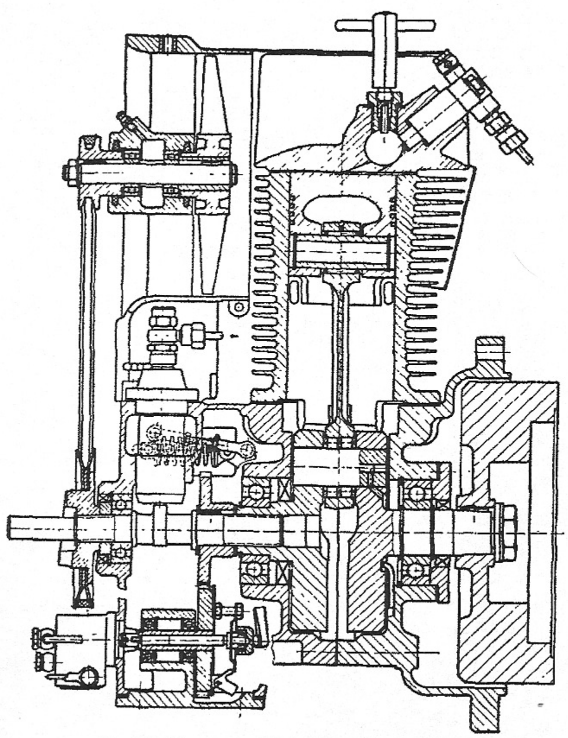


Fig. 16—Two-cycle Hirth 7-hp, 1-cyl engine

tive. Its specifications are:

Bore and stroke—3 × 3½ in.
Displacement—25 cu in. per cyl
Maximum speed—1800 rpm
Maximum net output—3.5 hp
Weight of complete single cylinder package—250 lb

The Enfield engine (Fig. 15), likewise built in Great Britain, represents another version of the same category. Aluminum is used to a somewhat wider extent for cooling fins and shrouds, thus improving performance and reducing weight. Much emphasis is laid on a neat appearance. The opposed

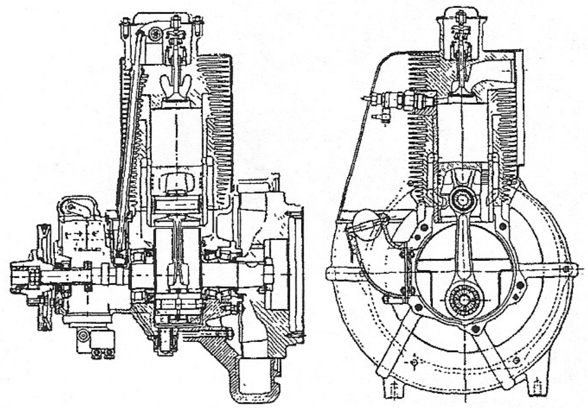


Fig. 17—Two-cycle Stihl 12-hp, 1-cyl engine

cylinder configuration of the twin results in a well-balanced, short engine:

Bore and stroke—3.35 × 3.9 in.
Displacement—34 cu in. per cyl
Maximum speed—1800 rpm
Maximum net output—6.5 hp per cyl
Weight—200 lb single, 310 lb twin

Small Size Air-Cooled Diesel Engines—The need for mechanization of the small farms in Europe led to the development of a special kind of small diesel engine, primarily of German origin. The common features of nearly all of these new engine types are:

1. Two cycle.
2. Six to twelve hp per cyl.
3. Single and twin cyl.
4. Approximately 30 cu in. per cyl.
5. Bmep, 43–65 psi.
6. Speed, 2000–3000 rpm.
7. Crankcase scavenged.

These engines use aluminum die castings to a wide extent and are thus light, simple, and easy to maintain. They are usually designed into a neat, compact power package. Resulting from the employment of crankcase scavenging, the crankshaft is built up from several individual pieces to facilitate space filling counterweights; and the use of antifriction bearings for crank and main bearings to permit metered fresh oil lubrication.

The Hirth engine (Fig. 16) is possibly the most simple design of all. Cylinder head, crankcase, and shrouds are aluminum die castings. The combustion chamber is of the swirl type, and the power package is distinguished by its neat appearance:

Bore and stroke—3.0 × 3.8 in.
Displacement—27 cu in. per cyl
Maximum speed—2200 rpm
Maximum net output—7 hp
Weight, including flywheel, filter, and cleaners—130 lb

The Stihl engine (Fig. 17) is characterized by its uniflow scavenge system. The combustion air enters through an automatic inlet valve in the crankcase. The exhaust gas leaves through an exhaust valve located in the center of the cylinder head.

The cylinder unit is of a rather unconventional design and comprises three parts:

1. A cast-iron cylinder liner, which has cooling fins around the combustion chamber and carries the injection nozzle.

2. A finned aluminum muff which is shrunk on the cylinder liner and includes the scavenging ducts from the crankcase to the cylinder liner.

3. An aluminum cylinder head which carries the exhaust valve and the disk-like combustion chamber.

This design, although more complicated and expensive, improves the scavenging efficiency and avoids the critical exhaust ports controlled by the piston crown. A higher than average continuous output is the result. Also, on this engine all major housings are aluminum die castings leading to a clean outline. The engine is built in single and twin cylinder type:

Bore and stroke—3.35 × 3.7 in.
Displacement—33 cu in. per cyl
Maximum speed—2200 rpm
Maximum net output—12 hp per cyl (corresponding to 65 psi at 1600 ft per min)

The Triumph engine (Fig. 18) did hold a particular position in the range of these small engines insofar as it was of the so-called "semidiesel" type. It was characterized by the low compression ratio of 11/1 combined with a sufficiently high surface temperature of the combustion chamber located in the cylinder head to initiate combustion. For this purpose, the aluminum cylinder head had a comparatively thick wall with restricted heat dissipation, except at the nozzle seat, which was surrounded by fins to keep the fuel injector cool. The combustion pressure did not exceed 750 psi, thus permitting a light weight structure. Combined with the comparatively high speed of 3000 rpm, a specific unit weight of 13 lb per hp was achieved. The engine had to be started with gasoline until the required temperature of the cylinder head was obtained. A small carburetor and a spark ignition system were provided for this purpose. Recently this engine has been modified to a normal diesel engine with a 16/1 compression ratio to eliminate the carburetor system. It is noteworthy that at the same time the output has been reduced to 10 hp at 2800 rpm. The Triumph's specifications are:

Bore and stroke—3.35 × 3.7
Displacement—33 cu in. per cyl
Maximum speed—3000 rpm
Maximum output—12 hp per cyl
Weight of complete power package—155 lb

The Gutbrod engine (Fig. 19) is another sample of small high-speed engines, shown in the 2-cyl version. The use of crankcase scavenging requires that the crankcase compartments be completely separated, leading to a rather expensive crankshaft and bearing configuration. There are four crankshaft bearings and the crankshaft is built up from seven parts. The engine is built in 1- and 2-cyl models. Its specifications are:

Bore and stroke—2.7 × 3.5 in.
Displacement—20 cu in. per cyl
Maximum speed—2700 rpm
Maximum output—6 hp per cyl
Weight of one cylinder—105 lb

Medium Size, Large Production Engine Families for a Wide Range of Applications—This is by far the predominant group of all aircooled diesel engines; certain families are produced in numbers up to 50,000 engines per year. It is characterized by:

1. Four cycle.
2. Good performance.
3. High speed.
4. Moderate weight.
5. Low price.
6. Ultimate standardization with families of one to twelve cylinders.
7. Aluminum cylinder head secured to the crankcase by necked-down cylinder attaching studs, using

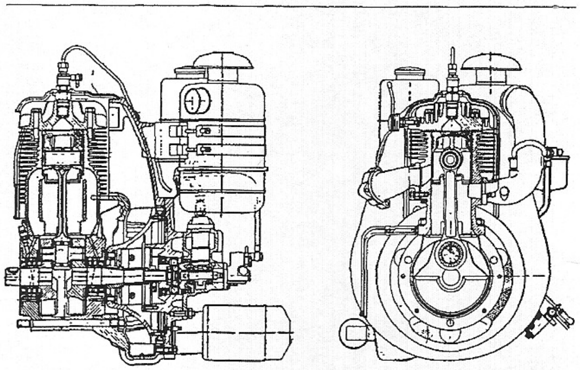


Fig. 18—Two-cycle Triumph 10-hp, 1-cyl engine

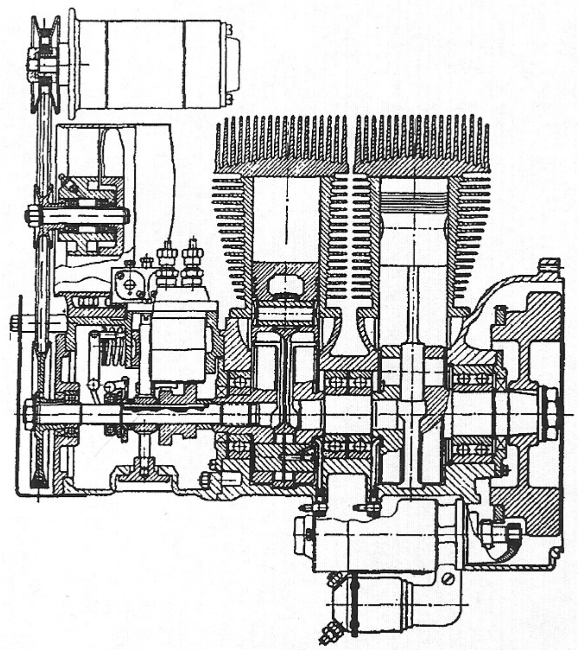


Fig. 19—Gutbrod 12-hp, 2-cyl engine

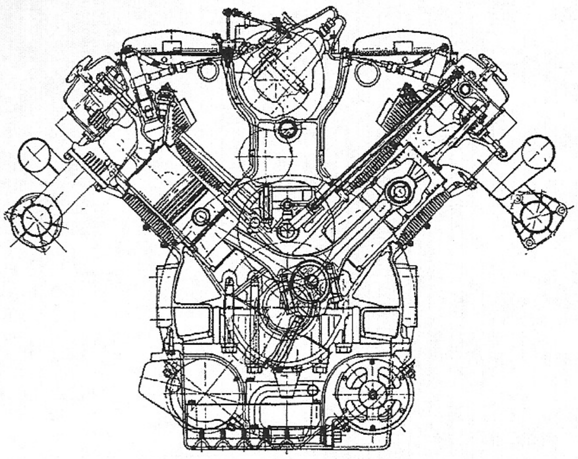


Fig. 20—Deutz V-style 6, 8, and 12-cyl engine

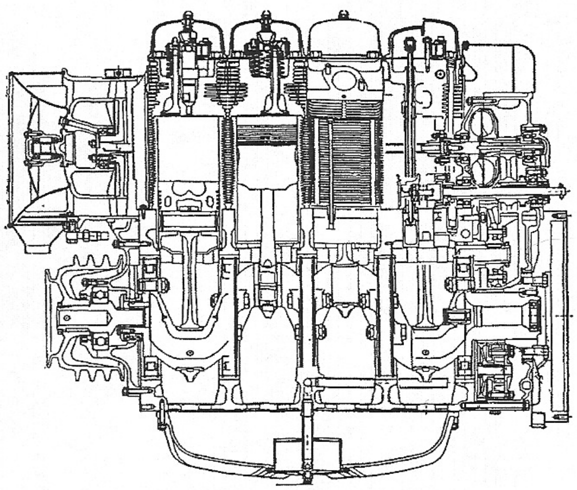


Fig. 21—Tatra 95-hp, 4-cyl engine

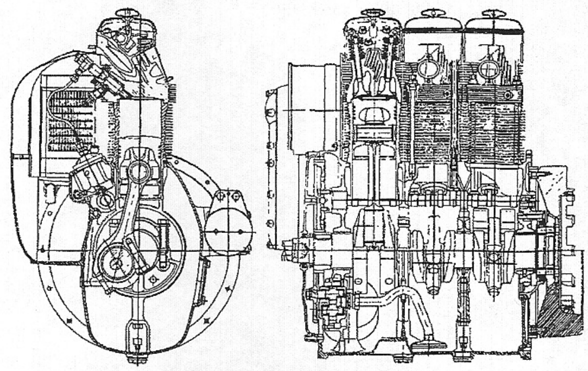


Fig. 22—Kaelble 60-hp, 3-cyl engine

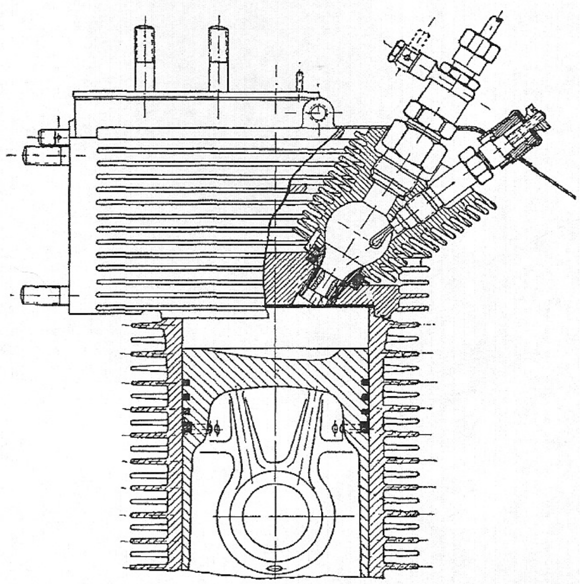


Fig. 23—MWM cylinder head section

the cast-iron cylinder barrel as a spacer under compression.

Typical for this group is the well-known family of Deutz in Germany (Fig. 20). All Deutz engines use a whirl-type combustion chamber, made from stainless steel and cast in the aluminum alloy cylinder head. The engines are designed with a view to low cost and high production volume:

Bore and stroke—4.4 × 5.5 in.
Displacement—81 cu in. per cyl
Maximum speed—2300 rpm
Maximum net output—21 hp per cyl
Turbocharged V-12—26 hp per cyl

Simple machining, wide use of sheet metal parts, and permanent mold castings serve this purpose. It is obvious that the same cylinder parts are used in engines with various numbers of cylinders. This family consists of 1-, 2-, 3-, 4-, and 6-cyl in-line configuration; 6-, 8-, and 12-cyl V-style configuration. The weight varies widely with the number of cylinders from 45 lb per hp for the single cylinder with 16 hp at 1800 rpm to 9 lb per hp for the turbocharged 12-cyl with 310 hp at 2300 rpm. These weight ratios illustrate clearly the influence of the number of cylinders and how carefully specific data must be evaluated if valid conclusions are to be drawn.

Tatra (Fig. 21), in Czechoslovakia, is another pioneer of aircooled engines. Its line of aircooled diesel engines presents many worthwhile features beyond those mentioned in the group specification. Tatra uses an open-chamber combustion system with direct injection. The aluminum crankcase is shaped as a tunnel housing with roller main bearings. The crankshaft is built up from individual cast-steel crankpin units, which are secured together by bolts, clamping the main roller bearings between crankcheeks. This construction results in a short power package, a stiff structure which is essential for aircooled diesel engines, and gives an exceptionally high degree of standardization using two crankshaft units for all in-line and V-style engines.

Another remarkable feature of the Tatra engines

is the control of the cooling air fan and supercharger drives by means of fluid couplings which are automatically operated by the cooling air temperature and engine load, respectively. The considerable fuel savings at part load and protection against overcooling obtained with such an arrangement will probably lead to general acceptance of this feature by other manufacturers. The family includes 1- and 4-cyl in-line and 6-, 8-, and 12-cyl V-style configuration. The two latter ones are also built with a mechanical blower. The engine's features:

Bore and stroke—4.7 × 5.1 in.
Displacement—90 cu in. per cyl
Maximum speed—2000 rpm
Maximum net output—23 hp per cyl
8 and 12 cyl—28 hp per cyl

The Kaelble engine (Fig. 22), manufactured in Germany, is another example of this category. The engine is interesting because of its fin arrangement across the valves and the tunnel crankcase with plain main bearings mounted in special bearing carriers. The combustion system is of the antichamber type with the antichamber cast in the aluminum head. The engine is built in 1-, 2-, 3-, and 4-cyl in-line models:

Bore and stroke—4.5 × 5.1 in.
Displacement—83 cu in. per cyl
Maximum speed—2300 rpm
Maximum net output—20 hp per cyl

Motoren-Werke Mannheim (Fig. 23), another German make, uses a particular antichamber design which permits operation on a wide range of fuels. An interesting feature is the separation of the combustion chamber from the cylinder head, thus simplifying the cylinder head casting. This engine model is planned to be built in 1-, 2-, 3-, 4-, 6-, 8-, and 12-cyl versions:

Bore and stroke—3.86 × 4.72 in.
Displacement—55 cu in. per cyl
Maximum speed—2200 to 2500 rpm
Maximum net output—12 hp to 15 hp

Fig. 24 shows the Swiss Locomotive Works 12-cyl opposed cylinder engine. Although still in the experimental stage, this design demonstrates the potential of the aircooled engine with regard to compactness of the power package. Engine is planned to be built in 4-, 6-, 8-, and 12-cyl models:

Bore and stroke—4.4 × 5.5 in.
Displacement—81 cu in. per cyl
Maximum speed—2200 rpm
Maximum net output—21 hp per cyl

Large Size, High Performance Engine Families, Primarily for Military Applications—The characteristic features of this group are:

1. Four cycle.
2. High performance.
3. Minimum weight.
4. Minimum bulk.
5. High speed.
6. Supercharged.
7. 27–60 hp per cyl.
8. Bmep up to 140 psi.
9. Piston speed 2300 fpm.
10. High standardization, families of 6-, 8-, and 12-cyl.
11. Design characteristics influenced by aircraft

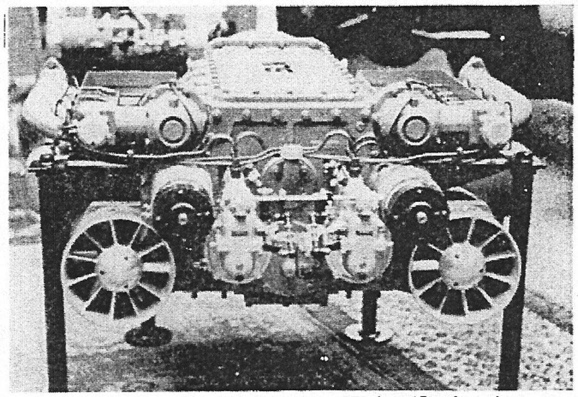


Fig. 24—Swiss Locomotive Works 250-hp, 12-cyl engine

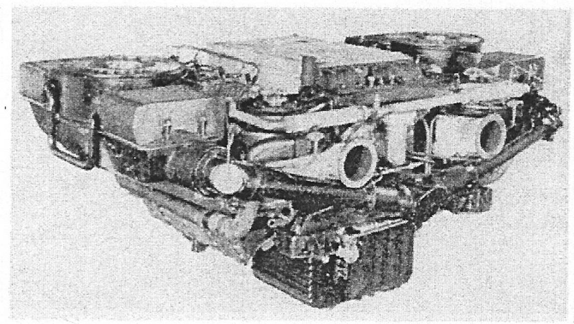


Fig. 25—Simmering Graz Parker 750-hp, 16-cyl tank engine, Austria

engine practice as: Use of aluminum wherever possible; use of high strength materials; cylinder unit, consisting of aluminum cylinder, head shrunk on steel cylinder barrel, secured to the crankcase by flange connection.

It is obvious that such features lead to a higher price per weight unit but not necessarily to a higher price per horsepower. However, the high ratings require periodical overhaul at shorter intervals than the engines for industrial uses and the medium sized engines. Because of the very specific military requirements, widely different engine models have been developed of which the following four examples may demonstrate the diversity of possible approaches.

Figs. 25 and 26 show a 750-hp, 16-cyl, turbocharged tank engine developed by Simmering Graz Pauker in Austria during World War II. The cylinders are arranged in four banks with 135- and 45-deg V-angle, respectively. Two vertical turbochargers provide the combustion air, two suction fans supply cooling air to the cylinders and oil coolers. The crankcase is fabricated steel. Three link connecting rods are attached to one master rod. The crankshaft has four cranks and five main bearings. The combustion system is of the antichamber type, the antichamber mounted separately on the cylinder head to facilitate the cylinder head finning. The engines features are:

Bore and stroke—5.3 × 6.3 in.
Displacement—2240 cu in.
Maximum speed—2000 rpm

Continued on page 224.

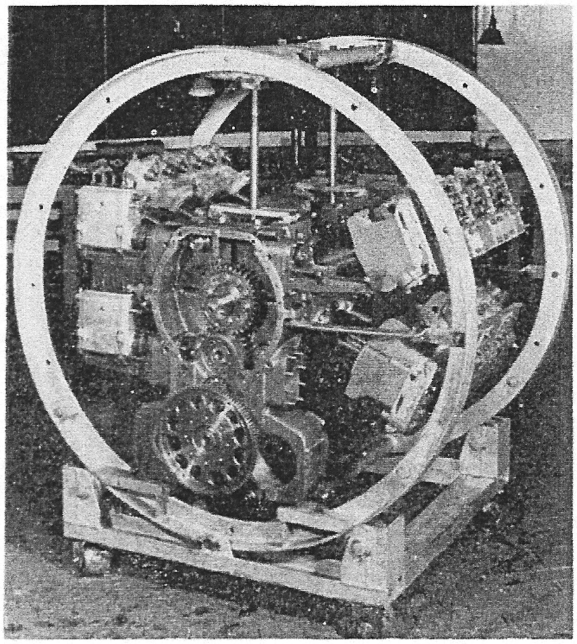


Fig. 26—Simmering Graz Parker 750-hp, 16-cyl bare engine, Austria

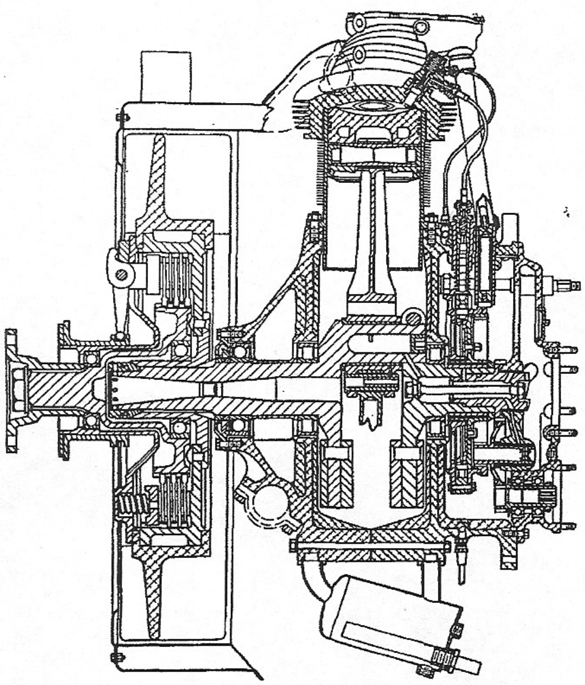


Fig. 28—Guiberson 245-hp, 9-cyl radial

Maximum gross output[3]—750 hp
Net weight—5300 lb (use of aluminum was limited to cylinder head and piston)

The Caterpillar radial tank engine (Fig. 27) was likewise developed during World War II. The engine design follows the usual pattern of radial aircraft engines, increasing the proportions according to the higher combustion loads of the diesel engine.

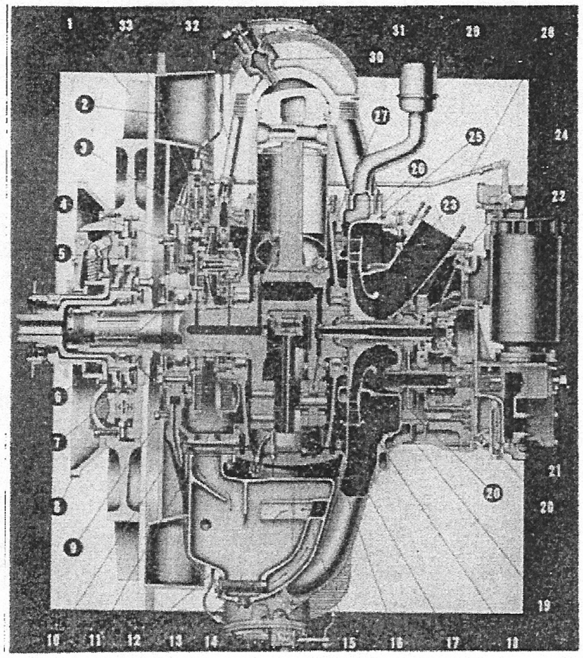


Fig. 27—Caterpillar 450-hp, 9-cyl radial

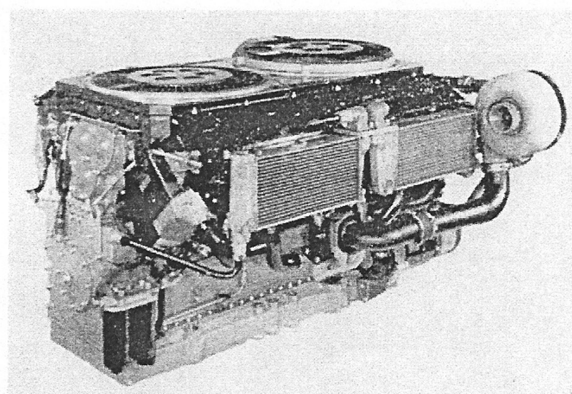


Fig. 29—Continental 750-hp, 12-cyl V-style engine

A finned precombustion chamber is screwed in the cylinder head. The engine is supercharged by a mechanically driven compressor. Its specifications are:

Bore and stroke—$6\frac{1}{8} \times 6\frac{7}{8}$ in.
Displacement—1823 cu in.
Maximum gross output[3]—520 hp
Maximum speed—2000 rpm
No. of cylinders—9
Total weight (approximately)—3200 lb

The Guiberson 9-cyl radial diesel engine (Fig. 28) was produced in small quantities before World War II for United States light tanks and undoubtedly would have been continued but for the policy decision to discontinue supply of diesel fuel for combat vehicle use. Its features were:

Bore and stroke—$5\frac{1}{8} \times 5\frac{1}{2}$ in.

[3] For tank engines gross maximum ratings are given because the required cooling horsepowers are widely dependent upon the particular installation.

Displacement—1020 cu in.
Maximum gross output[3]—245 hp at 2200 rpm
Weight—700 lb

The new Continental 750-hp tank engine (Fig. 29) has been described thoroughly in a recent SAE paper.[1] The engine is listed here as a representative of the V-style configuration which leads to a particularly compact power package with 5 lb per gross hp and 10 hp per cu ft of volume occupied by the power package:

Bore and stroke—5.75 × 5.75 in.
Displacement—1790 cu in.
12-cylinder
Maximum speed—2400 rpm
Maximum gross output[3]—750 hp
Weight of complete package—3800 lb

Summary

Aircooled diesel engines are coming into increased usage commercially and continued military applications of the principle can be expected because of the special demands of this service. Aircooled diesel engines are built with a great variety of features showing that most of the well-proved designs from liquid-cooled engine development may be used when applied carefully. The aircooled principle shows advantages in space utilization and in ability to handle hot and cold ambient temperatures. The liquid-cooled engines may be expected to continue their present commercial popularity until more extensive service records prove that the aircooled principle is superior.

Additional References

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2. *Product Engineering*, Vol. 23, January, 1952, pp. 150–151: "Diesel Engine Cooled by Forced Air."
3. SAE Transactions, Vol. 61, 1953, pp. 422–441: "Contemporary European Aircooled Diesel-Engine Practice," by W. H. Worthington.
4. *Automotive Industries*, Vol. 112, Jan. 1, 1955, pp. 92, 106: "Aircooled Automotive Diesels Introduced in England," by David Scott.
5. *The Engineer*, Vol. 199, May 6, 1955, pp. 643–645: "Air- and Water-Cooled Diesel Engines," by Helmut Meyer.
6. "The High Speed Aircooled Diesel Engine—Past and Present," by Richard Kloss. Paper presented at SAE New England Section Meeting, March 6, 1956.
7. *Oil Engine and Gas Turbine*, Vol. 24, January, 1957, pp. 346–347: "Aircooling for Vehicle Engines."
8. "European Developments in Small Aircooled Engines," by W. E. Meyer. Presented at SAE Summer Meeting, Atlantic City, June 2, 1957.

DISCUSSION

Describes Advantages of Aircooling on Military Vehicles

—Capt. Richard H. Sawyer
Ordnance Tank-Automotive Command,
U. S. Army

DESPITE the technical advantages which are more or less easily shown to accrue on aircooling, as far as the Army is concerned the basic advantage is reduction of logistic burden by the elimination of the fluids required by more conventional cooling systems.

This advantage is emphasized when one considers that military vehicles must be expected to operate in deserts and in Arctic areas without essential changes to meet different climatic conditions.

With the advent of very high output conventional engines or where high output is to be achieved through the use of unusual engine configurations to gain high displacement in a relatively small volume, aircooling appears to be put to a severe test. The army is attacking its dieselization program through parallel approaches involving aircooling and liquid cooling.

Military requirements for multifuel operation consider the ability to burn 83/91 octane gasoline, as well as JP-4 or conventional diesel fuels, as an essential criterion. Operation on gasoline must be achieved at a reasonably high power level and obtain a temperature range whose lowest value must be in the neighborhood of 0 F.

ORAL DISCUSSION

Reported by E. R. Donner
Standard Oil Co. of California

Wallace M. Brown, Pacific Car & Foundry Co.: Present design of the chassis makes it almost impossible to install aircooled engines in present day trucks.

Dr. F. W. Lohmann, Kloechner-Humboldt-Deutz AG and Diesel Energy Corp.: It is true that present-day design does not lend itself to installing aircooled engines where frames are designed for liquid-cooled engines.

W. P. Eddy, 1957 SAE President: What in your opinion has been done to develop a suitable liquid to operate as a coolant at 250 F?

Mr. Bachle: The coolant now available is ethylene glycol cooling up to 275–300 F. Trouble is encountered in the plumbing to handle these elevated temperatures.

Robert Niels, J. Niels Lumber Co.: We have a starting problem with fuels and lubricants at −40 F. Lubricants that are conducive to starting at low temperatures do not lend themselves to a safety factor at higher ambient temperatures.

Capt. Sawyer: The Army calls for fuels and lubricants to have a usable range from −65 to 125 F ambient temperatures.

Henry Ard, Potlatch Forests, Inc.: How is wear rate affected by aircooled engines?

Mr. Bachle: Aircooled engine fins can be tailored so as to give a maximum of cooling to all points.

Lloyd E. Johnson, Caterpillar Tractor Co.: We have trouble keeping dust and the like from clogging radiator. How do you control this in aircooled engines?

Dr. Lohmann: Aircooled engines have high velocity of air passing through the fins, thereby assisting to keep the fins clean. However, this does not help too much with straw and sticks, tumbleweed, and the like.

Mr. Bachle: Engines with a long fin design set up vibration which assists in keeping fins free from dust. However, on landing boats salt spray and/or water will clog fins very rapidly.

Fred H. Dodson, Division of Forestry Fire Control, State of California: How do you eliminate sand blasting in some sandy soil operations?

Mr. Bachle: Sand does no damage to cylinders, only to the fan. There are coatings on the market that will protect the fan.

Mr. Eddy: Fatigue failure from vibration is a problem in large aircooled engines. How do you compensate for this in the engines you refer to?

Mr. Bachle: The fins on the large engines are machined, whereas the fins discussed in my paper are cast. This gives them a larger and sturdier base.